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SIMPLIFIED ASSESSMENT OF COMBINED INTERVENTION FOR THE SEISMIC AND ENERGETIC RETROFIT OF A SCHOOL BUILDING IN PADUA (ITALY).

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Abstract. *According to European policies a reduction of 55% in CO_2 emissions is expected within 2030 and EU would be the first climate-neutral economy and society within 2050. The building and construction sector is responsible for 34% of final energy use and 37% of energy-related CO_2 emissions: improving envelopes and energy systems on existing buildings, thus, becomes a valid solution to implement European policies on climate change mitigation and adaptation to its effects. Furthermore, in the last years researchers and designers paid growing attention to combined seismic and energy intervention solutions, aiming at extending building heritage service life as well, by increasing its resilience and safety.*

In this paper a simplified and quick method for assessing energy and seismic retrofit intervention strategies is presented and applied to an existing school building owned by the Municipality of Padua (Italy). Performance indicators are assessed in separate phases and subsequently aggregated by means of a multi-attribute decision-making (MADM) method. Seismic vulnerability assessment returned a capacity-demand ratio, whereas energy efficiency improvement was assessed based on the annual primary energy reduction. By applying the TOPSIS multi-attribute method it was possible to aggregate performance values obtained in the previous phases; hence, a ranking was drawn up to evaluate the best-combined retrofit measure.

Keywords: Sustainability, Combined Retrofit, Simplified Assessment, School Building, Multi-criteria decision making.

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1 INTRODUCTION

In 2021 the buildings and construction sector was responsible for 34% of final energy consumption and 37% of energy-related CO_2 emissions (operational energy and process-related) [1]. In order to improve the sustainability of existing buildings and the related renovation actions, energy and structural solutions shall be considered and realized together. Other than reducing the energy consumption, the potential advantages related to combined interventions compared to uncoupled strategies include the reduction of social risks connected to seismic hazard together with the overall intervention costs, and an extension of buildings' lifespan [2]. Combined retrofitting technologies can be categorised into integrated exoskeleton, envelope and horizontal members (roof and ceilings) solutions: the systems may have different degree of integration and invasiveness [3]. National incentives for building restoration have been made available by European Member States' governments in the last decades, by means of policies, grants, low-interest loans and tax policies [4], thus encouraging private investment and reducing the retrofit cost barrier [5]. Nevertheless, these measures are often oriented to the energy performance improvement only, ignoring potential seismic losses [3]. In Italy the *Superbonus* scheme [6] provided a tax credit share of 110% to owners who incurred intervention costs aimed at improving the energy and seismic performance of a building.

One of the main issues related to the evaluation of the energy performance, thus to the Building Energy Simulations (BES), to achieve the goals of national and international directives, has always been the large amount of detailed input data required. The recent trend to move towards the simulation of groups of buildings to widen the single-building scale perspective increased this issue, since such detailed information represents a massive high-computational task for hundreds or thousands of buildings. One of the possible strategies to tackle this issue is to provide robust results with simpler models derived from the classical BES approaches that can simulate physical processes and building thermal behaviour solving energy balance. Among the tools developed to simulate large scale districts or groups of buildings that base their building energy simulation on detailed balance engines, such as UMI [7], CityBES [8], and CitySIM [9], a new tool based on lumped-capacitance parameters has been developed by the University of Padua. EUReCA [10] is a dynamic tool that reproduces an equivalent electrical network considering a thermal system with a discrete number of lumped parameters. Two different models have been implemented: the five resistances and one capacitance (5R1C) network, presented in the ISO 13790:2008 Standard [11] and the seven resistances and two capacitance (7R2C) network based on the German VDI 6007 Standard [12], which analyses separately adiabatic and non-adiabatic building structures providing more accurate results when compared to Energy Plus single-building simulations, as demonstrated by the reliable results shown by [13].

Similarly, the seismic vulnerability of buildings can be assessed by means of various methods, which can be divided in two main classes: empirical methods are based on statistical analyses of past earthquake-related damages, whereas analytical methods use mechanical properties to numerically compute a building's behavior; both of them can be applied, by adopting a hybrid approach [14]. The simplified procedures for the seismic vulnerability assessment of RC buildings only require a small amount of data compared to more detailed ones, thus making these suitable for macro-scale applications. Results coming from territorial-scale assessments may be used by decision-makers to identify the most vulnerable areas and to prioritize retrofit interventions [15]. Following this approach, a simplified displacement-based method was proposed by Crowley et al. [16], to relate the deformation potential to the fundamental vibration period of a building class, for each considered limit state: a set of mechanically-derived equations, able to determine the displacement capacity as a function of mechanical and geometrical properties, is applied, and the computed capacity can be compared to the displacement demand, thus returning a safety index. When dealing with territorial scale investigations, the amount and quality of information may vary. An attempt to overcome this limit was made by Cosenza et al. [17], who advanced a simplified procedure to assess the seismic capacity of existing RC buildings as an expression of base shear and global drift. According to this procedure, once the seismic capacity is computed for each building class, the dispersion of results is modulated according to the level of knowledge. An additional method, proposed by Gattesco et al. [18], consisted in assessing the seismic capacity of RC school buildings, by means of a simplified linear static analysis, accounting for the main collapse mechanisms of these structures (shear, bending-compression and local failures). This procedure can be applied on many structural types, including 3D frames and mixed walls buildings, returning as an output the resisting foot acceleration, to be compared to the expected site acceleration, in order to get the safety index.

In this paper a simplified procedure for the integrated assessment of energy and seismic performance of a school building is proposed. Three seismic and four energetic retrofit solutions were considered for the combined improvement of the building. The split values of energy and seismic performance were computed in the as-built and retrofitted configuration and then coupled, by implementing a multi-criteria decision-making method (TOPSIS). After selecting the representative criteria coming from the thermal and structural analyses, the weights were assigned to each criterion, trough a pairwise comparison approach, and a global performance coefficient was computed, to select the best combined retrofit alternative. To fully understand the potential of the results obtained, the analysis will be further improved and extended to a stock of buildings, representing a significant case study for policy makers and experts.

2 CASE STUDY AND SIMPLIFIED ASSESSMENT

2.1 The school building and the proposed retrofit solutions

The selected school is an L-shaped two stories building, with maximum dimensions in plan of 22.20 x 52.20 m and inter-story height of 3.20 m. It was built in 1966 and the structural resisting system, a 3D reinforced concrete (RC) frame, was designed to carry gravity loads only, according to the Italian design code in force between 1939 and 1971 [19]. Information regarding the structural system was obtained by the archive's documentation held by the Municipality of Padua (consisting in project drawings, technical reports, historical images and bill of quantities), together with the envelope's characteristics. Energy system's data, including heating and lighting features, were collected by an in-situ survey. The occupation was estimated to be about 250 people, including students and teachers.

The vertical bearing system is made of RC columns, with cross square sections ranging from 300 x 300 mm for the perimetral elements to 350 x 350 mm for the inner elements. Beams in the longitudinal direction present a T-shaped cross section, being the upper flange of 650 x 235 mm and the web of 350 x 515 mm; in the cross direction beams are made of rectangular sections of 250 x 550 mm. Envelope's features were retrieved from archive's documentation as well. Tab. 1 presents the main properties of the envelope's structures. A more detailed investigation on the seismic fragility of the analyzed case studies was reported in [20]. This building was part of a stock of schools surveyed and presented in [21].

In order to improve both the seismic behaviour and the energy efficiency, twelve retrofit solutions were identified, making the assumption that the intervention would be applied to the sole envelope, thus making the process less invasive and limiting possible interference with

Type of construction	Construction materials description	Thickness [m]	U-value [W/(m² K)]
External Wall	Exposed solid bricks wall, no insulation	0.27	1.85
Internal Wall	Solid bricks with cavity air gap (12-4-12 cm)	0.32	1.43
Ground Floor	Gravel floor, no insulation	0.40	2.03
Internal Ceiling	Brick-concrete ceiling, no insulation	0.36	1.11
Roof	Brick-concrete roof with crawl space, low insulation	0.58	0.38
Window	Double glazed, air filled, metal frame (4-16-4 mm)	0.24	3.70

Table 1: Properties of the building envelope.

the ongoing activities. Aiming at improving structural behaviour, shear walls were selected, supposing three different dispositions. In the first one the staircase was supposed to be replaced by RC walls and an additional wall was added on the south wing of the building, to move the stiffness center close to the mass center. A second disposition consisted in enlarging some columns placed on the east side of the school, thus obtaining new walls, without reducing the glazed surface. A third solution consisted in realizing long compact walls in both directions: a partial reduction of the glazed surface must be accounted in this case. Schematic drawings of the proposed structural retrofit measures can be seen in Fig. 1. According to the national directive [22], three solutions were proposed to increase the energy performance, consisting in replacing the windows with more insulated glazing (1.4 $W/(m^2K)$), insulating the external walls (0.15 $W/(m^2K)$), and the combination of both the previous retrofits. A fourth simple and cost-effective refurbishment strategy, consisting in replacing fluorescent lamps with LED ones, was considered. A list of the proposed uncoupled intervention is reported in Tab.2.

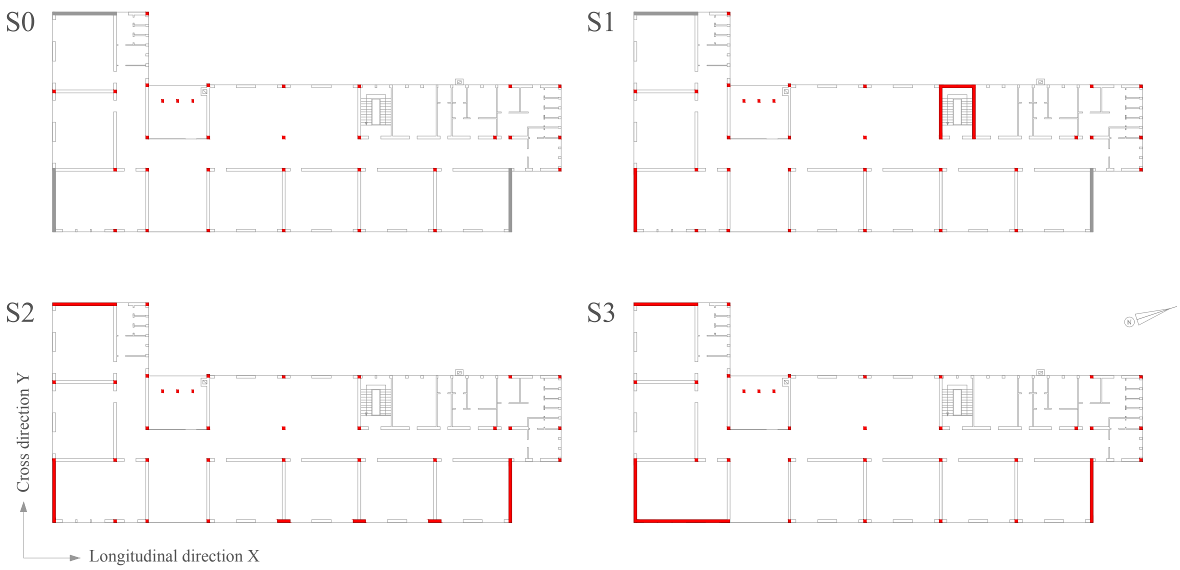

Figure 1: Plan views of the proposed seismic solutions.

2.2 Simplified seismic vulnerability assessment

Among the available procedures for the seismic vulnerability assessment of buildings, a simplified mechanical method was chosen: FIRSTEP-RC was developed by Gattesco et al. [18]

ID	Description
S0/E0	As built
S1	Staircase replaced by RC walls
S2	East side column enlargement
S3	Long compact walls
E1	Windows replacement
E2	Thermal insulation of external walls
E3	Thermal insulation of the external walls and windows replacement
E4	Replacement of fluorescent lamps with LED

Table 2: Proposed uncoupled retrofit solutions.

and it aims at assessing the seismic resistance of all kind of RC buildings (2D and 3D frames, walls, mixed systems). This procedure is quick to implement, due to the small amount of required data, and it is therefore suitable for macro-scale applications. A major simplification consists in assuming a strong similarity among the ground and upper floors: this assumption is verified when the vertical and horizontal elements' sections don't change significantly from floor to floor. The resisting force of the building F_R corresponds to that which lead to the collapse of the first element, defined as the minimum ratio between the resistance of each structural element F_{iu} and the horizontal action share f_{ie} acting on the same elements, as in Eq. (1). Once the behaviour factor q and the building mass W/g are computed, and the site parameters S and F_0 are set, the resisting foot acceleration of the whole building can be computed as in Eq. (2).

$$F_R = min\left(\frac{F_{iu}}{f_{ie}}\right) \tag{1}$$

$$a_u = \frac{F_R \cdot q \cdot g}{W \cdot S \cdot F_0} \tag{2}$$

So as to quantify the structural improvement obtained by the insertion of RC walls, the resisting foot acceleration a_u was chosen as a parameter and computed in the as-built and in the three retrofitted configurations. This value can be compared to the life-safety limit state (LLS) demand acceleration $a_{g,LLS}$, which for the Municipality of Padua equals $0.099g$, to define a safety index I_S, as reported in Eq. (3). The seismic performance parameter ζ is taken as the minimum value among $I_{S,X}$ and $I_{S,Y}$.

$$I_S = \frac{a_u}{a_{g,LLS}} \qquad \zeta = min(I_{S,X}, I_{S,Y}) \tag{3}$$

2.3 Simplified energy consumption assessment

The model selected to run the energy simulation is the 7R2C model implemented in EUReCA, an Urban Building Energy Simulation tool developed by the Authors in previous works [10, 13]. This model belongs to the class of the lumped-parameter networks, physic dynamic models where heat losses through the building envelope are considered by means of equivalent thermal resistances of each building structure. In this specific version, the building is modeled using a single thermal zone, which corresponds to 7 resistances coupled with 2 thermal capacities that account for the thermal response of the structures. To create this equivalent network, the first necessary input is the geometry of the case study presented, that is created extruding the building footprint (stored in a GeoJSON georeferenced file) by the height of the building.

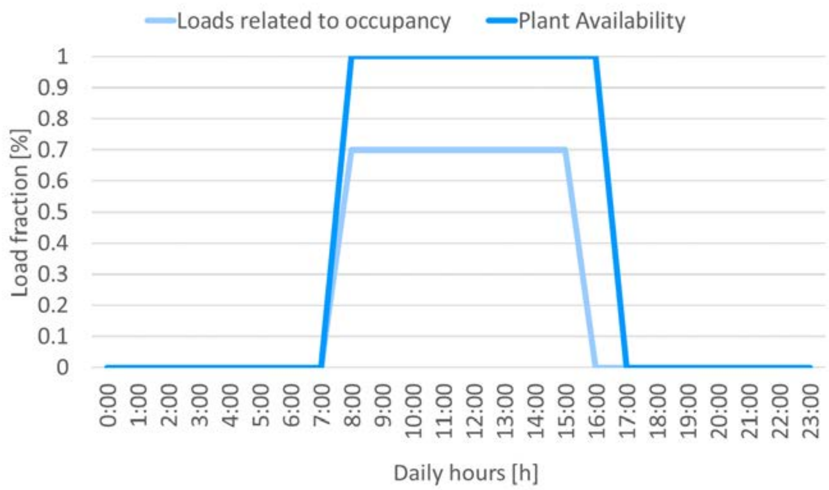

Figure 2: Operating schedules

The building constructions and the hourly usage are then associated to run the dynamic calculation. Concerning the latter, internal heat gains such as lighting, appliances and occupancy density have been set considering the information collected during onsite surveys and metered bills. The schedules of internal loads depend on the working hours of the school, and thus are related to the occupancy of people. Similarly, heating set-point temperatures and plant availability schedules have been defined according to the real operating conditions of the case study. Table 3 reports the input defined, while the related schedules have been reported in Figure 2. Nor cooling system nor mechanical ventilation system were considered because not present in the school. Further information and details on the model can be found in [13]. Simulations have been carried out for a typical climate of the Italian climatic zone E [23].

Occupancy (Sensible) $[W/m^2]$	Lighting $[W/m^2]$	Appliances $[W/m^2]$	Infiltration Flow Rate $[Vol/h]$	Heating set point $[°C]$
32.5	5.0	6.0	0.2	20.0

Table 3: Definition of internal loads and set-point temperature.

3 PERFORMANCE VALUES AND MULTI-CRITERIA INTEGRATION

Aiming at combining seismic and energy performances and costs obtained from simplified models, multi-criteria decision-making (MCDM) methods may be useful for this purpose. It's not uncommon, indeed, to deal with retrofit solutions that could significantly improve building seismic behaviour and its efficiency, while being expensive to implement: multi-criteria assessments are helpful when dealing with conflicting criteria, as in this case. Such methods are widely used to solve similar problems in different fields, including agricultural [24], transportation [25], energy [26] and construction [27] sectors. Among the different methods, the TOPSIS one, developed by Hwang and Yoon [28] was chosen: it only requires few parameters to be implemented, and the ensuing results are easy to understand. Weights assignment issue was tackled according to the procedure proposed by Saaty [29] in the context of the Analytic Hierarchy Process method (AHP), namely the pairwise comparison. More details on the TOPSIS method and weights assignment are reported in this section.

3.1 The TOPSIS method

The *Technique of Order Preference Similarity to the Ideal Solution* (TOPSIS) method is one of the most used methods in multi-attribute decision-making (MADM) domain [30]. The central idea of this method is that the optimal alternative is the one which is closer to the ideal (best) solution and further from the inferior (worst) solution [28].

It is based on five computation steps [31]: a decision matrix **D** is built, by assigning performance values x_{ij} of the different criteria to each alternative (*i*); then, these values are normalized by means of Eq. (4), to compare the values on different measure units (*ii*); normalized values r_{ij} are multiplied by the weights, thus the weighted normalized decision matrix **V** is obtained (*iii*); ideal and inferior solutions A^+ and A^- are defined, and euclidean distances d_i^+ and d_i^- of each alternative from ideal and inferior solutions are hence calculated as in Eq. (6) (*iv*); finally, the relative closeness coefficient C_i, ranging between 0 and 1, is computed for each action according to Eq. (7) (*v*).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{M} x_{ij}^2}} \qquad v_{ij} = w_j \times r_{ij} \tag{4}$$

$$A^+ = (v_1^+ \dots v_N^+) \qquad A^- = (v_1^- \dots v_N^-) \tag{5}$$

$$d_i^+ = \sqrt{\sum_{j=1}^{N} (v_i^+ - v_{ij})^2} \qquad d_i^- = \sqrt{\sum_{j=1}^{N} (v_i^- - v_{ij})^2} \tag{6}$$

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{7}$$

In the present study, twelve alternatives (Tab. 4), each of which corresponds to a combined retrofit measure, were defined by coupling seismic strengthening and energy efficiency solutions. The outputs coming from the simplified structural analyses and energy simulations were used as input performance values together with intervention costs, in order to perform the multi-attribute assessment. In particular, five criteria were identified as relevant (see Tab.5), that are the structural performance, expressed by the capacity-demand ratio ζ, the energy efficiency improvements, conveyed by means of primary energy reduction ΔE_P and energy cost saved ΔE_{CS}, and the seismic C_S and energetic C_E intervention costs.

Alternative nr.	01	02	03	04	05	06	07	08	09	10	11	12
Str. solution	S1	S1	S1	S1	S2	S2	S2	S2	S3	S3	S3	S3
Ener. solution	E1	E2	E3	E4	E1	E2	E3	E4	E1	E2	E3	E4

Table 4: The twelve proposed combined retrofit alternatives.

Type	Symbol	Description	Pos/Neg	Weight w_j
Seismic	ζ	Capacity-demand ratio	Positive	33%
Energy	ΔE_P	Primary energy reduction	Positive	33%
Energy	ΔE_{CS}	Energy monetary savings	Positive	5%
Cost	C_S	Seismic retrofit cost	Negative	14%
Cost	C_E	Energy retrofit cost	Negative	14%

Table 5: Adopted criteria for multi-attribute assessment and weights assigned.

3.2 Weights assignment

Assigning different weights to each criterion is a step of fundamental importance when dealing with multi-criteria problems. Weights express the relative importance of each criterion compared to the others, which depends on the decision-maker's priorities and intentions.

In this paper the approach proposed by Saaty [29] was adopted, consisting in a pairwise comparison of the criteria. In order to assign these weights, for each couple of criteria a judgement on the relative importance of the first criterion compared to the second one is expressed by the decision-maker. According to the assessment scale proposed by the same author, the intensity of importance ranges from 1 (equal importance) to 9 (extreme importance). The output of a pairwise comparison is the matrix **P**, whose entries p_{ij} describe the decision-maker's preferences. It is appropriate to notice that in the pairwise comparison matrix all the comparisons are positive quantities, the elements on the main diagonal are 1 (since a criterion is compared to itself) and the matrix is reciprocal (the upper triangle is the reverse of the lower triangle). According to the decision-maker, the pairwise comparison matrix was built by assuming that structural safety and energy efficiency (expressed by capacity-demand ratio ζ and primary energy reduction ΔE_P) are more important than any other criteria; on the other hand, cost savings related to the energy use reduction ΔE_{CS} have the lowest relative importance. Moreover, intervention costs are of secondary importance, compared to the structural and energetic performance criteria. The weights are then obtained by calculating the eigenvector corresponding to the highest eigenvalue λ_{max}. Comparison values and the weights obtained are reported in Tab.6.

Criterion	ζ	ΔE_P	ΔE_{CS}	C_S	C_E	Weights w_j [%]
ζ	1.00	1.00	5.00	3.00	3.00	33
ΔE_P	1.00	1.00	5.00	3.00	3.00	33
ΔE_{CS}	0.20	0.20	1.00	0.33	0.33	5
C_S	0.33	0.33	3.00	1.00	1.00	14
C_E	0.33	0.33	3.00	1.00	1.00	14

Table 6: Pairwise comparison matrix **P** and weights w_j (λ_{max} = 5.06, IR = 1.2%).

Once the matrix is complete, possible contradictions in the entries are detected by performing a consistency check. Matrix inconsistency may depend on lack of information, vaguely defined problems, uncertain information or lack of concentration. Matrix consistency may be quantified by means of the consistency index IC defined in Eq. (8), as a function of the highest eigenvalue λ_{max} and the number n of criteria, which is 5 in this case. This index is to be compared with a random index RI of a matrix of order 5, which equals 1.11 according to [29]. The inconsistency ratio IR, obtained by dividing IC over RI, indicates how inconsistent the considered matrix is, compared to the average inconsistency of 500 matrices filled with random preference values [31]. If the aforementioned ratio IR is lower than 10%, the selected weights are accepted, otherwise different comparison values might be chosen by the decision-maker until the consistency check is satisfied.

$$IC = \frac{\lambda_{max} - n}{n - 1} \tag{8}$$

$$IR = \frac{IC}{RI} \tag{9}$$

4 RESULTS

4.1 Seismic assessment results

The seismic performance ratio ζ was selected as representative of the seismic improvement, to be adopted in the multi-criteria analysis. A synoptic table of the structural proposed solutions together with the corresponding seismic safety index and investment cost are reported in Tab.7.

By replacing the staircase with RC walls (scenario S1), the seismic behaviour significantly improved in both directions; nevertheless, a lower increase in safety index was observed in the longitudinal direction X, thus ζ value equals to 37.9%. According to scenario S2, the longitudinal direction X is still weaker than the cross direction Y, with higher values of ζ ratio, which equals 61.3% in this case. Finally, a major improvement is achieved by applying scenario S3: the worst behavior is in the cross direction Y, with a safety index of 71.9% in the same direction. Average values reported in local price list were adopted, in order to assess the structural intervention cost. An overall cost of 490 €/m^3 (including the demolition of non-structural bricks and the construction of new RC structures) was accounted to estimate the intervention cost.

ID	Alias	$F_{R,X}$ [kN]	$F_{R,Y}$ [kN]	W [kN]	$a_{u,X}$ [g]	$a_{u,Y}$ [g]	$I_{S,X}$ [%]	$I_{S,Y}$ [%]	C_S [€]
S0	As-built	212.3	172.9	13'070	0.0063	0.0051	6.4	5.2	-
S1	Stairs	1358.1	2975.4	13'949	0.0375	0.0821	37.9	82.9	20'072
S2	Columns	2186.3	3437.1	13'861	0.0607	0.0955	61.3	96.5	23'046
S3	Walls	4967.9	2594.9	14'034	0.1363	0.0712	137.7	71.9	26'711

Table 7: Safety indexes and costs for each seismic retrofit scenario.

4.2 Energy simulation results

The main goal of the simulations for the case study presented was to evaluate the current energy needed for space heating and the potential energy savings achievable with the application of the retrofit scenarios considered (Table 2). The cooling energy demand has not been considered for the analysis since the school does not have an HVAC system providing space cooling or mechanical ventilation. The model of the baseline case estimated a gas consumption of 9138 Nm^3 and an electric consumption of 19728 kWh. Simulations concerning the retrofit analysis were carried out by applying the energy conservation measures as a single action to estimate the impact on energy saving. Table 8 reports the main results obtained: scenario E1 lead to a reduction of gas consumption ΔE_G of 10% compared to the baseline, while the application of scenario E2 can achieve a 38% gas reduction, mainly due to the higher area involved in the retrofit actions. The combination of the two strategies to evaluate a complete refurbishment of the building envelope (scenario E3) resulted in a reduction of gas use of 51%. Supposing to provide other simple and cost-effective refurbishment strategies, the replacement of fluorescent lamps with LED (scenario E4) can reduce the electric energy used ΔE_{EL} by about 31%.

The impact of each scenario can be seen by looking at the primary energy reduction ΔE_P, obtained from the national conversion coefficients (1.05 for natural gas, 2.42 for electric energy). The highest energy saving (34%) is again achievable by reducing the overall thermal transmission losses, i.e., insulating both the opaque and the glazed surfaces. As a consequence, scenarios E1 and E2 are responsible for less consistent primary energy savings if applied separately. Similarly, the action on the lighting of the building has a significantly smaller impact when converted to primary energy, but can still contribute to the building refurbishment with a low investment cost C_E. Even if the variability of the energy costs during previous months does not allow a precise evaluation of the cost saving ΔE_{CS}, an economic analysis is still provided for completeness, considering the second semester of 2022 average costs from EUROSTAT [32]. The assumption is 0.077 €/kWh for natural gas and 0.295 €/kWh for electricity. Moreover, the total investment cost for the wall insulation and window substitution has been set according to average technical values and the local price list for public administrations, and it is 80 €$/m^2$ for wall insulation and 800 €$/m^2$ for window substitution.

ID	Alias	ΔE_G [Nm³]	ΔE_{EL} [kWh]	ΔE_P [kWh]	ΔE_{CS} [€]	C_E [€]
E0	As-built	-	-	-	-	-
E1	Windows	946 (10%)	-	9946 (7%)	729	161’065
E2	Envelope	3458 (38%)	-	36404 (25%)	2669	63’867
E3	Win. & Env.	4644 (51%)	-	48908 (34%)	3586	224’932
E4	Lighting	-	6069 (31%)	14687 (10%)	1790	28’659

Table 8: Energy reduction and costs for each energy retrofit scenario.

4.3 Decision matrices and final ranking

The decision matrix **D** collects the information on each alternative, according to a specific criterion. The entries of this matrix (performance values, x_{ij}) are expressed in different measurement units, thus a normalization step has to be implemented, by applying the Eq. 4 to every performance value. These are, hence, weighted according to the corresponding criterion weight. Then, the ideal A^+ and inferior A^- virtual solutions are defined, by taking the best and worst weighted and normalized performance values for each criterion.

The distances from ideal and inferior solutions are, hence, calculated for each alternative according to Eq. (6). When the euclidean distance from the ideal solution d_i^+ of a given alternative is lower, the same alternative will have a higher position in the ranking. On the other hand, when the distance from the ideal solution is higher, an alternative will have a lower position in the ranking. Analogous remarks can be made considering the euclidean distance from the inferior solution d_i^-. A full ranking of the alternatives is, finally, returned by computing the relative closeness C_i (score) of each solution (see Eq. (7)) to the ideal one. The best solution is that one with the highest score. The value of C_i ideally ranges from 0 to 1, where 0 corresponds to the score of the inferior solution (euclidean distance from the ideal solution is maximum) and 1 is the score of the ideal solution (euclidean distance from the ideal solution is minimum). The final ranking of the proposed alternatives is reported in Tab. 10.

Alternative	ζ [%]	ΔE_P [%]	ΔE_{CS} [€]	C_S [€]	C_E [€]
01	37.9	6.9	729	20'072	161'065
02	37.9	25.4	2669	20'072	63'867
03	37.9	34.1	3587	20'072	224'932
04	37.9	10.2	1790	20'072	28'659
05	61.3	6.9	729	23'046	161'065
06	61.3	25.4	2669	23'046	63'867
07	61.3	34.1	3587	23'046	224'932
08	61.3	10.2	1790	23'046	28'659
09	71.9	6.9	729	26'711	161'065
10	71.9	25.4	2669	26'711	63'867
11	71.9	34.1	3587	26'711	224'932
12	71.9	10.2	1790	26'711	28'659

Table 9: Decision matrix **D**.

Position	Alternative	C_i	Structural solution	Energy solution
I	10	0.725	Walls	Envelope
II	6	0.700	Columns	Envelope
III	11	0.691	Walls	Win. & Env.
IV	7	0.675	Columns	Win. & Env.
V	3	0.599	Stairs	Win. & Env.
VI	2	0.580	Stairs	Envelope
VII	12	0.438	Walls	Lighting
VIII	8	0.403	Columns	Lighting
IX	4	0.340	Stairs	Lighting
X	9	0.318	Walls	Windows
XI	5	0.254	Columns	Windows
XII	1	0.139	Stairs	Windows

Table 10: Ranking of the alternatives.

The following considerations can be drawn on the proposed solutions.

- The best intervention alternative (position I, C_I = 0.725) corresponds to solution number 10, in which the construction of compact RC walls (S3) is combined with the thermal insulation of the envelope (E2). By analyzing in detail the performance values of this retrofit measure, a notable increase can be observed on a seismic level in terms of safety index I_S (ζ value increased from 5.2% to 71.9%); the primary energy reduction ΔE_P is considerable, as well, and equals 25.4% compared to the as-built conditions. The total estimated intervention cost is equal to 90'578 € and the annual energy monetary savings ΔE_{CS} is of 2669 €. The identified optimal solution, hence, guarantees good levels of seismic safety and energy efficiency, while containing the intervention costs. Nevertheless, on a functional level this wouldn't be the best solution, since it would lead to a partial reduction of the school's glazed surface, thus lowering the natural illumination of two south-facing classrooms.

- The second best alternative (position II, C_{II} = 0.700) is number 6, in which the columns enlargement (S2) is combined with the thermal insulation of external walls (E2). Although the seismic performance is lower in this case, compared to the alternative number

10 (ζ ratio equals 61.3% for solution number 6), the primary energy reduction ΔE_P and the energy cost savings ΔE_{CS} are equal to the previous case, since the energetic retrofit solution is the same. Still, the overall intervention cost is slightly lower (the total amount is of 86'913 €); this difference is justified by a reduction in the quantities of needed material. Furthermore, this solution does not result in a reduction of the glazed surface, as it replaces non structural walls portions with RC volumes connected to the existing columns, while keeping the opaque surface unvaried.

- Non optimal solutions (C_{III} = 0.691 and C_{IV} = 0.675) correspond to the alternatives 11 and 7, in which the construction of compact walls (S3) and columns enlargement (S2) are coupled with the simultaneous installation of thermal insulation and new glazings (E3). The closeness coefficient values C_i of the alternatives at issue are not so different from those of the two best alternatives. In both cases, the seismic features are unvaried compared to the alternatives 10 and 6, respectively. The concurrent application of new envelope and windows, instead, brings a benefit in terms of primary energy reduction (ΔE_P = 34.1%) and annual monetary savings (ΔE_{CS} = 3587 €) in cases 11 and 7, while increasing the overall intervention cost, which totally amounts to 251'643 € for solution number 11 and 247'978 € for solution number 7. The relatively huge difference compared to the options 10 and 6 is due to windows installation. Again, it is appropriate to remark that option 11, unlike option 7, would reduce some portions of the glazed surface in the south side of the building, thus affecting the natural illumination of some classrooms.

- The worst solutions correspond to the remaining ones: please refer to Tab. 10 for the closeness coefficients C_i and to Tab. 9 for the performance values. Among the aforementioned alternatives, number 3 and 2 are in V and VI place: both the alternatives implement the staircase reconstruction retrofit (S1), for which the seismic performance ratio ζ equals to 37.9%, in the face of a structural intervention cost C_S which is just slightly lower than that related to the construction of RC walls and columns enlargement interventions. Then, solutions 12, 8 and 4 are in VII to IX place: a major disadvantage of these alternatives lies in the fact that replacing traditional lights with LED ones (E4) is definitely the most economically convenient (see C_E performance values for LED alternatives), but low values of primary energy reduction ΔE_P and monetary energy savings ΔE_{CS} are not compensated by improving the seismic performance. Nevertheless, the replacement of traditional lighting with LED lamps could be implemented independently from the envelope retrofit. Finally, retrofit options 9, 5 and 1 are in the last positions (from X to XII): this is due to the fact that the solely windows replacement (E1) results in a high C_E cost, against negligible variations in primary energy ΔE_P and energy cost savings ΔE_{CS}.

5 CONCLUSIONS

A simplified method for the selection of the optimal combined seismic and energy retrofit measure of existing buildings was proposed in this paper. The method was applied to a primary school, owned by the Municipality of Padua (Italy), presenting poor seismic and energetic performance. Three seismic and four energetic retrofit solutions were proposed, which resulted in twelve combined intervention alternatives. The seismic vulnerability was assessed by means of a simplified mechanical method, which only requires a small amount of data, and is, therefore, suitable for macro-scale applications. A simplified energy consumption assessment was carried out by means of EUReCA, a dynamic tool that reproduces an equivalent electrical network considering a thermal system with a discrete number of lumped parameters. The structural and energetic intervention costs were estimated, according to local price list.

In order to integrate the seismic and energy performance values and the intervention costs obtained from simplified models, thus to identify the best combined alternative, a multi-criteria decision analysis was performed. The TOPSIS method was chosen: this is based on the assumption that the optimal solution is the closest one to ideal (best) solution and the furthest from the inferior (worst) solution. Criteria weights were assigned based on the pairwise comparison approach, assuming that the structural safety and energy efficiency were more important than any other criteria. The inconsistency of the resulting comparison matrix was quantified and verified to be acceptable. Finally, the twelve alternatives' closeness coefficients C_i (scores) were computed, in order to obtain an ordered ranking of the same alternatives.

The optimal solution was identified as that one with the highest score. Results showed that the optimal solution guarantees good levels of seismic safety and energy efficiency, while containing the overall intervention costs. Nevertheless, this solution would lead to a partial reduction of the glazed surface, thus lowering the natural illumination of two classrooms. The second best alternative implements a different seismic retrofit measure, compared to the previous one: it solves the inconvenience of glazed surface reduction and the intervention cost is slightly lower; still, the seismic performance is not as high as the optimal solution. Non optimal alternatives are still valid retrofit solutions, but higher intervention charges shall be incurred, due to the concurrent installation of envelope insulation and low-transmittance windows. The poorest solutions are those alternatives which minimize the costs at the expense of performances, and those which present a considerable cost while providing scarce benefits in terms of seismic safety and/or energy efficiency.

In order to increase the knowledge of methods for the integrated assessment of seismic and energetic performance on a territorial scale, further deepening is needed on simplified assessment of structural and thermal behavior of school buildings. Including a wider range of selection criteria in the multi-criteria analysis, such as environmental impact, damage-related economical losses (EALs), available incentives and building downtime, would be useful to account for more information on the proposed combined alternatives, giving the DM a more detailed perspective on the optimal solution. Furthermore, the adoption of different MCDM methods may lead to slightly different results in the final ranking: the sensitivity of the chosen method should be assessed by comparing results coming from different integration strategies. Finally, different profiles for the decision-maker should be defined (by assigning different entries to the comparison matrix) and original combined intervention solutions could be contemplated.

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